Ain Shams Engineering Journal (2015) xxx, xxx–xxx

Ain Shams University

Ain Shams Engineering Journal

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www.sciencedirect.com

MECHANICAL ENGINEERING

Thermal induced motion of functionally graded beams subjected to surface heating

Pravin Malik *, **Ravikiran Kadoli** [1]

Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal, Srinivasnagar, 575025, India

Received 7 May 2015; revised 29 August 2015; accepted 12 October 2015

KEYWORDS

Thermal induced motion;
Functionally graded beams;
Finite element analysis;
Surface heating

Abstract Thin beam of the functionally graded (FG) type subjected to a step heat input on one surface and insulated or exposed to convective heat loss on the opposite surface is under consideration for the evaluation of thermal induced motion. The dynamic displacement and dynamic thermal moment of the beam are analysed when the temperature gradient is independent of the beam displacement. The power law index dictates the metal–ceramic distribution across thickness of the beam and its effect on the thermal vibration of the beam is examined. The article discusses, in depth, the influence of various factors such as length to thickness ratio of beam, heat transfer boundary conditions, physical boundary conditions, and metal–ceramic combination on the thermal oscillations of FG beam. It is found that attenuation of the amplitude of static thermal deflection and superimposed thermal oscillations is a strong function of the metal–ceramic combination for the FG beam.

1. Introduction

Structural elements subjected to high temperature, severe temperature gradient, and uneven heating rates are unavoidable during the operation of gas turbines, nuclear reactors, castings, forgings, radiant burners, pipes in heat exchangers, artillery barrels, etc. Sharp temperature gradients in the structural elements arise due to sudden exposure to very large amount of heat which is observed during launching of rocket, space craft structural components subjected to radiant solar heat (Yu [1] and Thornton et al. [2]), sudden load fluctuations on nuclear reactor, heat exchangers (Hong et al. [3]), friction generated heat in rotors of turbogenerator (Jevti et al. [4]) and during heat treatment of cast and forged components, etc. Thermal induced motion and their control are important to avoid catastrophic malfunctioning of various precision instruments and accessories in satellites. Pioneering research by Boley [5], Boley and Barber [6] and Boley [7] on thermally induced vibrations of beam provides a detailed inter-relation of time dependent temperature variation on the structural vibrations. Boley [5] considered the problem of lateral vibration of a thin beam with simple supports and subjected to rapid heat flux on the upper surface and thermally insulated condition on the bottom. Boley [5] proved that the time dependent thermal moment acts as a forc-

* Corresponding author. Tel.: +91 9823861312.
E-mail addresses: pravin_malik@yahoo.com (P. Malik), rkkadoli@rediffmail.com (R. Kadoli).
[1] Tel.: +91 9844400659.

Peer review under responsibility of Ain Shams University.

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http://dx.doi.org/10.1016/j.asej.2015.10.010
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ing function to induce a structural deformation and for thicker beams the inertia effect can be neglected and the dynamic solution approaches the static solution. After establishment of this original work in 1956, other researchers were motivated to probe the thermally induced vibrations in other structures and/or with different thermal/mechanical boundary conditions. Considering the presence and absence of the inertial effects Boley and Baber [6] investigated the dynamic displacement of beams and plates when subjected to step heat input. The role of inertia was found to be important for rapidly applied heat input and for thin plates. In a similar article, Boley [7] describes an approximate method to study the thermally induced vibrations of beams and plates under the influence of damping and axial (or in-plane) load. Researches of Boley [5,7] and Boley and Barber [6] reveal that the occurrence of thermally induced vibrations depends on a non-dimensional parameter B which is the ratio of the thermal response time of the structure to the structural response time. Further, it is shown that the existence of thermally induced vibrations depends only on B and as this parameter increases, inertia forces disappear. Manolis and Beskos [8] have worked on the problem attempted by Boley [5] using Laplace Transform and discussed the effects of axial load, internal viscoelastic damping and external viscous damping on thermal vibrations of simply supported beam subjected to rapid heating. Apart from structures which are subjected to radiant/-surface heating, structures undergoing internal heating may also experience thermally induced vibrations [9,10]. Blandino and Thornton [9] have carried out a detailed study on the thermally induced vibration caused by internal heating. The analysis showed that the natural frequency of the beam was more important than the heating rate in determining whether vibrations occur. The steady-state vibration amplitude is reached when the internal heating is balanced by convection from the beam surface. Malik et al. [10] reported their findings related to the effect of boundary conditions on thermally induced vibrations of isotropic beam subjected to internal heating and convective heat loss. It was observed that the boundary conditions influence the magnitude of dynamic displacement and dynamic thermal moment. A sustained thermally induced motion is observed with progress of time when the temperature gradient being evaluated is dependent on the forced convection generated due to beam motion. Finite element analysis on the transient behaviour of aluminium and graphite epoxy plates subjected to an instantaneously imposed heat flux has been reported by Chang et al. [11].

During the last two decades, materials with gradation in properties are being developed and one such material is functionally graded material (FGM), typically like the one that caters to high temperature, good wear resistance, in conjunction with high strength and toughness. FGMs were proposed in Japan during 1984–1985 for the space plan project. FGMs are a class of composites that have a continuous variation of material properties from one surface to another. The smooth transition between metallic and ceramic components reduces thermal stresses, residual stresses and stress concentration factors found in laminated composites. With the developments in manufacturing processes, special varying gradients can be achieved to suit various goals of engineering applications as presented by Sobczak and Drenchev [12]. These materials can be fabricated by varying the percentage content of two or more materials such that the new materials have the desired property gradation in spatial directions. FGMs have gained widespread applicability as thermal-barrier, wear and corrosion resistant coatings. Yet another application of FGM is thin-walled members such as plates and shells, which are used in reactor vessels, turbines and other machine parts that are susceptible to instabilities due to buckling load and large amplitude deflections, or excessive stresses induced by thermal or combined thermo-mechanical loading.

In view of the above developments vast research on the static and dynamic analysis of functionally graded material structures such as beams and plates has been attempted. Thai and Vo Thuc [13], and Sina et al. [14] have analytically investigated the effects of boundary conditions, volume fraction and shear deformation on natural frequencies, and mode shapes on the bending and free vibration of FGM beams. Simsek et al. [15] analysed the influence of volume fraction index, material properties, length scale parameter, aspect ratio and Poisson's effect on the static bending behaviour of FGM beams and showed that the deflections of the microbeam by the classical beam theory are always larger than those by the modified couple stress theory. Under the influence of a moving harmonic load, Simsek and Kocaturk [16] analysed free vibration characteristics and dynamic behaviour of a FG simply supported beam. The system of equations of motion was derived using Lagrange's equation under the assumptions of Euler–Bernoulli beam theory. It was observed that the effects of different material distribution, velocity of the moving harmonic load and excitation frequency play very important role on the dynamic behaviour of the FGM beam. Malekzadeh and Shojaee [17] showed that under the influence of moving heat source, the amplitude of centre deflection decreases by increasing the velocity of heat source and convective heat transfer coefficient. Wattanasakulpong et al. [18] analysed the linear thermal buckling and vibration characteristics of thick FG beams and found that the fundamental frequency decreases with the increase in temperature and tends towards minimum point closing to zero at the critical temperature while in the post-buckling region, the fundamental frequency increases with the increase of temperature. The elasticity solutions of a transversely loaded Euler–Bernoulli FGM beam were obtained by Sankar [19] assuming exponential variation of Young's modulus and the stress concentration effects were studied by loading the beam on softer and harder side. Sankar and Tzeng [20] showed that the thermoelastic properties of beam can be tailored to reduce the thermal residual stresses for a given temperature distribution which can be accomplished by varying the thermoelastic constants in a manner opposite to the gradation of temperature through the thickness. As far as thermal vibrations of plates are concerned, Shen [21] revealed that the width-to-thickness ratio of a plate, plate aspect ratio as well as the volume fraction distribution have a significant effect while control voltage has a minor effect on the thermal bending response of FGM plates. Sohn and Kim [22] analysed static and dynamic stabilities of FG panels under supersonic air flows considering temperature and volume fraction changes and showed that FG panels are more stable than the isotropic metal panel, in terms of thermal post-buckling characteristics. Yang et al. [23] have investigated the large amplitude vibration of initially stressed FGM laminated rectangular plates with thermo-electro-mechanical loading and demonstrated that the linear and non-linear vibration behaviour of the pre-stressed laminated plates is greatly influenced by the various factors such as vibration amplitude and material composition. The thermal shock